CP Violation: The CKM Matrix and New Physics

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Recent measurements of CP violating asymmetries have led to a significant progress in our understanding of CP violation. The implications of the experimental results for the Kobayashi-Maskawa mechanism and for new physics are explained.

1. Introduction

The study of CP violation is, at last, experiment driven. Experiments have measured to date three independent CP violating parameters:

• Indirect CP violation in $K \to \pi\pi$ [1] and in $K \to \pi\ell\nu$ decays is given by

$$|\varepsilon| = (2.28 \pm 0.02) \times 10^{-3}. \tag{1}$$

• Direct CP violation in $K \to \pi\pi$ decays is given by

$$\mathcal{R}e(\varepsilon'/\varepsilon) = (1.66 \pm 0.16) \times 10^{-3}. \tag{2}$$

(The world average given in eq. (2) includes the new result from NA48 [2], $\mathcal{R}e(\varepsilon'/\varepsilon) = (1.47 \pm 0.22) \times 10^{-3}$, and previous results from NA31, E731 and KTeV.)

• The CP asymmetry in $B \to \psi K_S$ decay (and other, related, modes) has been measured:

$$\mathcal{I}m\lambda_{\psi K} = 0.734 \pm 0.054. \tag{3}$$

(The world average given in eq. (3) includes the new results from Belle [3], $\mathcal{I}m\lambda_{\psi K} = 0.719 \pm 0.074 \pm 0.035$, and Babar [4], $\mathcal{I}m\lambda_{\psi K} = 0.741 \pm 0.067 \pm 0.033$, and previous results from Opal, Aleph and CDF.)

In addition, CP asymmetries in many other modes (charged B decays and neutral B decays into final CP eigenstates and non-CP eigenstates) have been searched for. We describe the implications of the new data for our theoretical understanding of CP violation.

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2. Standard Model Lessons

Within the Standard Model, the only source of CP violation is the Kobayashi-Maskawa (KM) phase [5]. This phase appears in the CKM matrix which describes the charged current interactions of quarks.

2.1. Unitarity Triangles

The CKM matrix gives the couplings of the W^+-boson to $\bar{u}_i d_j$ quark pairs:

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}. \tag{4}$$

The unitarity of the matrix leads to various relations among its elements, *e.g.*,

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0. \tag{5}$$

The *unitarity triangle* is a geometrical presentation in the complex plane of the relation (5). It provides a convenient tool in the study of flavor physics and CP violation:

1. Flavor changing processes and unitarity give rather precise information on the magnitudes of all elements except for $|V_{ub}|$ and $|V_{td}|$, which have large uncertainties. The unitarity triangle is a pictorial way of combining the various constraints on these elements and of testing whether the constraints can be explained consistently within the CKM framework.

2. The angles of the triangle are related to CP violation. In particular, measurements of various CP asymmetries in B decays can be used to constrain the values of these angles. Conversely,

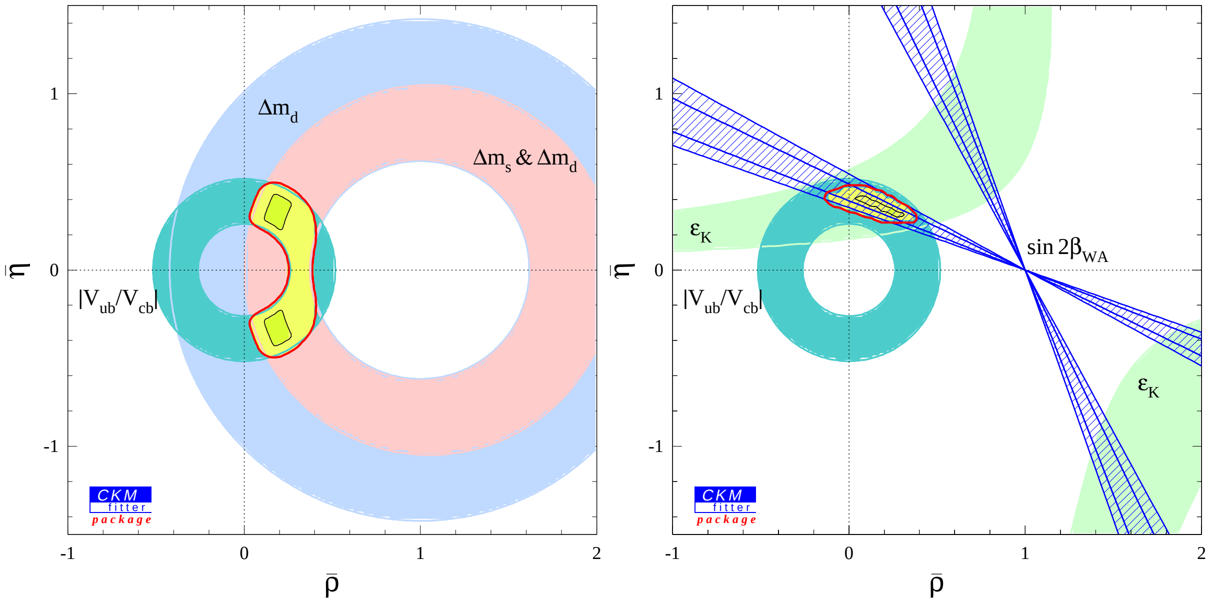


Figure 1. Constraints on the $(\bar{\rho}, \bar{\eta})$ parameters from tree processes and from (left) CP conserving loop processes (Δm_B, Δm_{B_s}) and (right) CP violating processes (ε, $\mathcal{I}m\lambda_{\psi K}$).

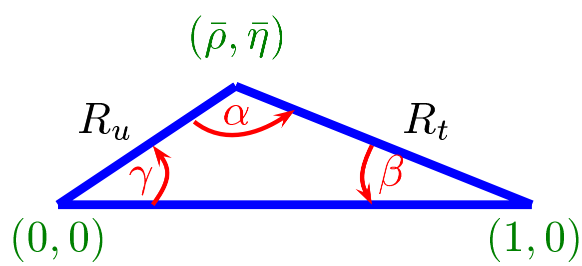
the consistency of the various constraints tests whether CP violation can be accounted for by the Kobayashi-Maskawa mechanism.

Since the length of one side, $|V_{cd}V_{cb}|$, is well known, it is convenient to re-scale the unitarity triangle by the length of this side and put it on the real axis. When doing so, the coordinates of the remaining vertex correspond to the ρ and η parameters in the Wolfenstein parametrization [6] of the CKM matrix (or, in an improved version [7], to $\bar{\rho} = (1 - \frac{\lambda^2}{2})\rho$ and $\bar{\eta} = (1 - \frac{\lambda^2}{2})\eta$):

$$V = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}. \quad (6)$$

The angles α, β and γ (also known as, respectively, ϕ_2, ϕ_1 and ϕ_3) are defined as follows:

$$\alpha \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right), \quad \beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right),$$
$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right). \quad (7)$$



The lengths R_t and R_u are defined as follows:

$$R_t \equiv \left|\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right|, \qquad R_u \equiv \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right|. \quad (8)$$

In what follows, we present the constraints on the $(\bar{\rho}, \bar{\eta})$ parameters coming from various classes of processes. (The plots have been produced using the CKMFitter package [8].)

In Figure 1 we compare the constraints from CP conserving processes to those from CP violating ones. The CP conserving observables are the mass difference in the neutral B system, Δm_B,

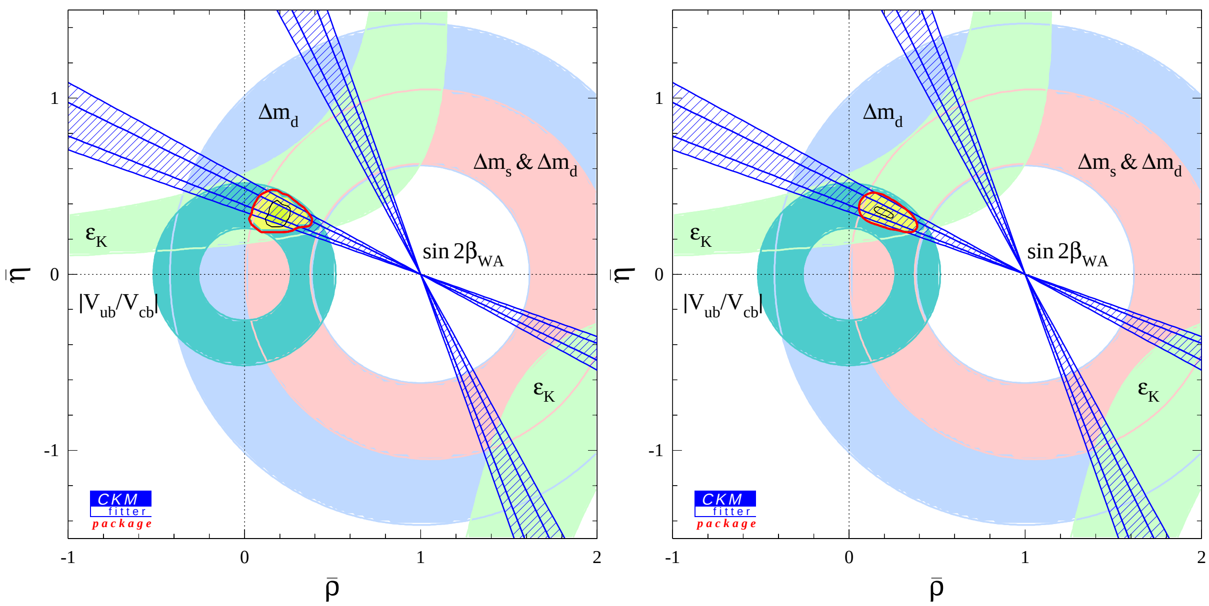


Figure 2. Constraints on the $(\bar{\rho}, \bar{\eta})$ parameters from (left) CP conserving and the ε observables compared to the $\mathcal{I}m\lambda_{\psi K}$ constraint, and (right) from all observables.

and the lower bound on the mass difference in the B_s system, Δm_{B_s}. The CP violating observables are the indirect CP violation in $K \to \pi\pi$ decays, ε, and the CP asymmetry in $B \to \psi K_S$ decays, $\mathcal{I}m\lambda_{\psi K}$. There are two important lessons to be drawn from this comparison:

- Since there is a significant overlap between the allowed regions in the two panels, we learn that the two sets of constraints are consistent with each other. Thus it is very likely that the KM mechanism is indeed the source of the observed CP violation.

- The constraints from the CP violating observables are stronger than those from the CP conserving ones. While the allowed ranges are related to the experimental accuracy, an important factor in this situation is the fact that CP is a good symmetry of the strong interactions. (The effects of $\theta_{\rm QCD}$ are irrelevant to meson decays.) Consequently, some CP asymmetries can be theoretically interpreted with practically zero hadronic uncertainties.

Another way to see the consistency of the KM picture of CP violation is the following. Within the Standard Model, there is a single CP violating parameter. Therefore, roughly speaking, a measurement of a single CP violating observable simply determines the value of this parameter. This situation is demonstrated in the left panel of Figure 2, where the constraints from all but the $\mathcal{I}m\lambda_{\psi K}$-measurement are used to produce an allowed range in the $(\bar{\rho}, \bar{\eta})$ plane. A second measurement of a CP violating observable tests this mechanism, as demonstrated in the same Figure by overlaying the constraint from the measurement of $\mathcal{I}m\lambda_{\psi K}$. (It is amusing to note that in ref. [9], the allowed range for $\mathcal{I}m\lambda_{\psi K}$ from the fit to all other observables is quoted to be $0.734^{+0.055}_{-0.045}$, to be compared with the range from the direct measurements in eq. (3).) The allowed region in the $(\bar{\rho}, \bar{\eta})$ plane from the combination of all observables is shown in the right panel of

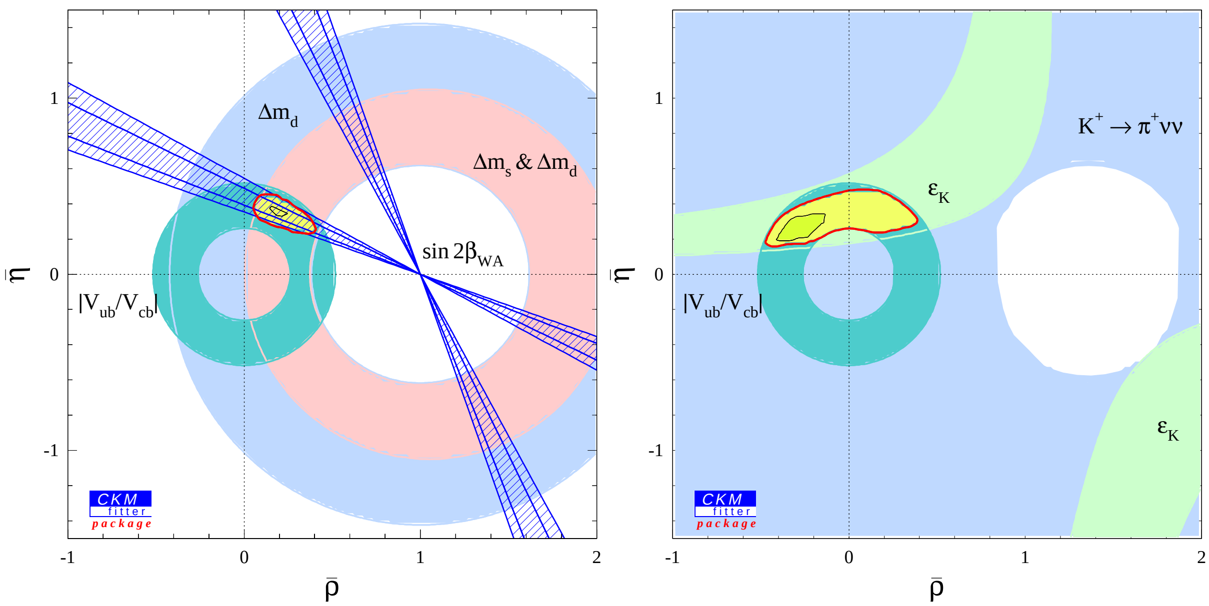


Figure 3. Constraints on the $(\bar{\rho}, \bar{\eta})$ parameters from (left) B physics (Δm_B, Δm_{B_s}, $\mathcal{I}m\lambda_{\psi K}$), and (right) K physics (ε, $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$).

Figure 2. We can again draw several conclusions:

- The CKM matrix provides a consistent picture of all the measured flavor and CP violating processes.
- The recent measurement of $\mathcal{I}m\lambda_{\psi K}$ adds a significant constraint.

In Figure 3 we make one final comparison, between observables related to B physics (Δm_B, Δm_{B_s}, $\mathcal{I}m\lambda_{\psi K}$, left panel) and to K physics (ε, $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ [10], right panel).

The conclusions that we draw from this comparison are the following:

- There is no signal of new flavor physics.
- At present, the constraints from B physics are much stronger. Future measurements of $\mathcal{B}(K \to \pi\nu\bar{\nu})$ (for both the charged and the neutral modes) will be essential to make this comparison into a useful probe of new physics.

2.2. Testing the KM mechanism

Since, by the consistency between the predicted range and the measured value of the CP asymmetry in $B \to \psi K_S$, the KM mechanism of CP violation has successfully passed its first precision test, we are able to make the following statement:

Very likely, the KM mechanism is the dominant source of CP violation in flavor changing processes.

Thirty eight years have passed since the discovery of CP violation [1] and twenty nine years have passed since the KM mechanism has been proposed [5]. But only now, following the impressively precise measurements by Belle and Babar that yield (3), we can make the above statement based on experimental evidence. This is a very important step forward in our theoretical understanding of CP violation.

We would like to emphasize, however, three important points in the above statement:

1. *'Very likely:'* since we are using only two CP violating observables, the consistency of

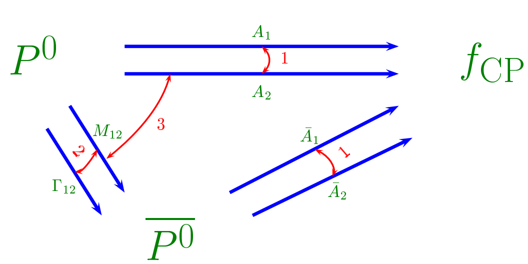
the KM picture could be accidental. Additional measurements are crucial to make a more convincing case for the validity of the KM mechanism.

2. *'Dominant:'* the accuracy of the Standard Model prediction for $\mathcal{I}m\lambda_{\psi K}$ is of $\mathcal{O}(20\%)$. Therefore, it is quite possible that new physics contributes to meson decays at this level.

3. *'Flavor changing:'* while we have good reasons to think that flavor changing CP violation is dominated by Standard Model processes, the situation could be very different for flavor diagonal CP violation. Here, the KM mechanism predicts unobservably small CP violation, while new physics can dominate such observables by several orders of magnitude. Future searches of EDMs are crucial to clarify this point.

3. General Lessons

CP violation in meson decays is a complex phenomenon. This is best demonstrated by examining CP violation in neutral meson decay into a final CP eigenstate. (P stands here for any of the K, D, B and B_s mesons.)



Each arrow in this figure stands for an amplitude that carries an independent CP violating phase. The various interferences between the different paths from P^0 to $f_{\rm CP}$ yield three distinct manifestations of CP violation:

1. *In decay:*

$$\left|\frac{\bar{A}}{A}\right| \neq 1 \quad \left[\frac{\bar{A}}{A} = \frac{\bar{A}_1 + \bar{A}_2}{A_1 + A_2}\right]. \tag{9}$$

2. *In mixing:*

$$\left|\frac{q}{p}\right| \neq 1 \quad \left[\left(\frac{q}{p}\right)^2 = \frac{2M_{12}^* - i\Gamma_{12}^*}{2M_{12} - i\Gamma_{12}}\right]. \tag{10}$$

3. *In interference (of decays with and without mixing):*

$$\mathcal{I}m\lambda \neq 0 \quad \left[\lambda = \frac{q}{p}\frac{\bar{A}}{A}\right]. \tag{11}$$

One of the beautiful features of CP violation is that experiments can measure each of these three types separately. Take for example B meson decays:

1. The CP asymmetry in charged B decays is sensitive to only CP violation in decay:

$$\begin{aligned} \mathcal{A}_{f^\mp} &\equiv \frac{\Gamma(B^- \to f^-) - \Gamma(B^+ \to f^+)}{\Gamma(B^- \to f^-) + \Gamma(B^+ \to f^+)} \\ &= \frac{|\bar{A}_f/A_f|^2 - 1}{|\bar{A}_f/A_f|^2 + 1}. \end{aligned} \tag{12}$$

2. The CP asymmetry in semileptonic neutral B decays is sensitive to only CP violation in mixing:

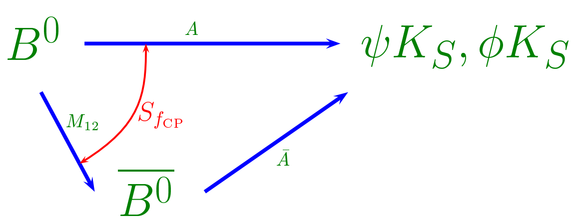
$$\begin{aligned} \mathcal{A}_{\rm SL} &\equiv \frac{\Gamma(\bar{B}^0_{\rm phys} \to \ell^+ X) - \Gamma(B^0_{\rm phys} \to \ell^- X)}{\Gamma(\bar{B}^0_{\rm phys} \to \ell^+ X) + \Gamma(B^0_{\rm phys} \to \ell^- X)} \\ &= \frac{1 - |q/p|^4}{1 + |q/p|^4}. \end{aligned} \tag{13}$$

3. The CP asymmetry in neutral B decays probes separately $|\lambda|$ (a combination of CP violation in mixing and in decay) and $\mathcal{I}m\lambda$ (purely CP violation in the interference of decays with and without mixing) [11–13]:

$$\begin{aligned} \mathcal{A}_{f_{\rm CP}}(t) &\equiv \frac{\Gamma(\bar{B}^0_{\rm phys} \to f_{\rm CP}) - \Gamma(B^0_{\rm phys} \to f_{\rm CP})}{\Gamma(\bar{B}^0_{\rm phys} \to f_{\rm CP}) + \Gamma(B^0_{\rm phys} \to f_{\rm CP})} \\ &= -C_{f_{\rm CP}} \cos(\Delta m_B t) + S_{f_{\rm CP}} \sin(\Delta m_B t) \\ C_{f_{\rm CP}} &= -\mathcal{A}_{f_{\rm CP}} = \frac{1 - |\lambda_{f_{\rm CP}}|^2}{1 + |\lambda_{f_{\rm CP}}|^2}, \\ S_{f_{\rm CP}} &= \frac{2\mathcal{I}m\lambda_{f_{\rm CP}}}{1 + |\lambda_{f_{\rm CP}}|^2}. \end{aligned} \tag{14}$$

Note that Babar's $C_{f_{\rm CP}}$ corresponds to Belle's $-\mathcal{A}_{f_{\rm CP}}$. Further note that the latter notation suggests that this CP asymmetry is analogous to $\mathcal{A}_{f\mp}$ measured in charged B decays. Formally, $\mathcal{A}_{f_{\rm CP}}$ measures deviations of $|\lambda|$ from unity while $\mathcal{A}_{f\mp}$ measures deviations of $|\bar{A}/A|$ from one. However, the deviation of $|q/p|$ from unity is known to be $\lesssim \mathcal{O}(10^{-2})$ and, given the present sensitivity of searches for $\mathcal{A}_{f_{\rm CP}} \neq 0$, can be safely neglected. In practice, therefore, the analogy is justified.

There is a class of CP asymmetries in neutral meson decays into final CP eigenstates that theorists love most. It involves decays where the direct decay amplitude is dominated by a single weak phase, so that CP violation in decay can be neglected ($|\bar{A}/A| = 1$) and where the effect of CP violation in mixing can be neglected ($|q/p| = 1$). In this case $|\lambda| = 1$, and the only remaining CP violating effect is $S_{f_{\rm CP}} \neq 0$.



The reason that this case is the theorists' favorite is that the theoretical interpretation, in terms of Lagrangian parameters, is uniquely clean. Explicitly, the asymmetry can be expressed purely in terms of the (CP violating) phase difference between the mixing amplitude and twice the decay amplitude:

$$S_{f_{\rm CP}} = \mathcal{I}m\lambda_{f_{\rm CP}} = \pm\sin[\arg(M_{12}^*) - 2\arg(A_{f_{\rm CP}})], \quad (15)$$

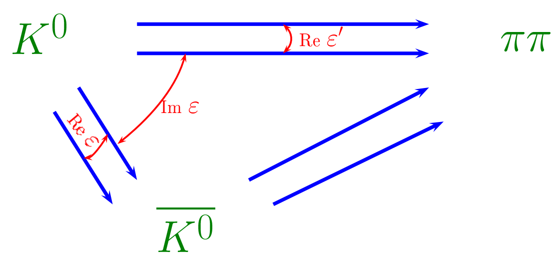
where the sign depends on the CP eigenvalue of the final state. Among the few modes that belong to this class are the $B \to \psi K_S$, $B \to \phi K_S$ [14,15] and $K \to \pi\nu\bar{\nu}$ [16] decays.

3.1. $K \to \pi\pi$

All three types of CP violation have been measured in $K \to \pi\pi$ decays. Historically, a different language has been used to parametrize the various CP violating observables. The translation between that language and our language is straightforward:

$$\varepsilon = \frac{1-\lambda_0}{1+\lambda_0}, \qquad \varepsilon' = \frac{1}{6}(\lambda_{00} - \lambda_{+-}), \quad (16)$$

where the subindex 0 refers to final two pions in an isospin-zero state, while the $+-$ and 00 subindices refer to, respectively, $\pi^+\pi^-$ and $\pi^0\pi^0$ final states.



The experimental values of the ε and ε' parameters are given in eqs. (1) and (2). The measurement of ε in 1964 constituted the discovery of CP violation and drove, through the work of Kobayashi and Maskawa, to the prediction that a third generation exists. The precise measurement of $\mathcal{R}e(\varepsilon'/\varepsilon)$ has important implications:

- Direct CP violation has been observed.
- The superweak scenario [17] is excluded.
- The result is consistent with the SM predictions.
- Large hadronic uncertainties make it impossible to extract a useful CKM constraint. This is the reason that no ε' constraint appears in our unitarity triangles.
- New physics (*e.g.* Supersymmetry [18]) may contribute significantly.

3.2. $B \to \psi K_S$

The $B \to \psi K_S$ decay [14,15], related to the $\bar{b} \to \bar{c}c\bar{s}$ quark transition, is dominated by a single weak phase. An amplitude carrying a second, different phase, is suppressed by both a CKM factor of $\mathcal{O}(\lambda^2)$ and a loop factor. Consequently, the deviation of $|\bar{A}_{\psi K}/A_{\psi K}|$ from unity is predicted to be below the percent level. It is then expected that $|\lambda_{\psi K}| = 1$ to an excellent approximation. This golden mode belongs then to the 'clean' class described above: $S_{\psi K} = \mathcal{I}m\lambda_{\psi K}$ and can be cleanly interpreted in terms of the difference between the phase of the $B^0 - \overline{B^0}$ mixing amplitude and twice the phase of the $b \to c\bar{c}s$ decay amplitude.

It would be nice to confirm this expectation in a model independent way. The present average over the Babar [4] and Belle [3] measurements is

$$|\lambda_{\psi K}| = \left|\frac{q}{p}\frac{\bar{A}_{\psi K}}{A_{\psi K}}\right| = 0.949 \pm 0.039. \qquad (17)$$

The central value is five percent away from unity with an error of order four percent. While this result is certainly consistent with $|\lambda_{\psi K}| = 1$, it does not yet confirm it. We would like to argue that the information from two other, entirely independent measurements constrains the deviation of $|\lambda_{\psi K}|$ from one to a much better accuracy. The first measurement is that of the CP asymmetry in semileptonic B decays. The world average over the results from Opal, Cleo, Aleph and Babar (see [19] and references therein) is given by

$$\mathcal{A}_{\rm SL} = 0.002 \pm 0.014. \qquad (18)$$

Through eq. (13) we can constrain the size of CP violation in mixing:

$$|q/p| = 0.999 \pm 0.007. \qquad (19)$$

The second measurement is that of the CP asymmetry in the charged mode, $B^\mp \to \psi K^\mp$:

$$\mathcal{A}_{\psi K^\mp} = 0.008 \pm 0.025. \qquad (20)$$

(This is the average over Cleo [20] and Babar [21] measurements.) Through eq. (12), and using isospin symmetry to relate this measurement to the neutral mode [22], we can constrain the size of CP violation in decay:

$$|\bar{A}_{\psi K}/A_{\psi K}| = 1.008 \pm 0.025. \qquad (21)$$

Together, eqs. (19) and (21) give

$$|\lambda_{\psi K}| = 1.007 \pm 0.026. \qquad (22)$$

This is a much stronger constraint than (17) and allows us to confidently use $|\lambda_{\psi K}| = 1$ from here on. This exercise carries an important lesson: the two measurements employed here provide only upper bound on asymmetries that are not subject to a clean theoretical interpretation. Yet, they take us a step forward in our understanding of CP violation. Indeed, each and every measurement contributes its part to solving the big puzzle of CP violation.

What do we learn from the measurement of $\mathcal{I}m\lambda_{\psi K} = 0.734 \pm 0.054$?

- CP violation has been observed in B decays.
- The Kobayashi-Maskawa mechanism of CP violation has successfully passed its first precision test. Figure 2 makes a convincing case for this statement.
- A significant constraint on the CKM parameters $(\bar{\rho}, \bar{\eta})$ has been added. Within the Standard Model,

$$\lambda_{\psi K_{S,L}} = \mp\left(\frac{V_{tb}^* V_{td}}{V_{tb}V_{td}^*}\right)\left(\frac{V_{cb}V_{cd}^*}{V_{cb}^*V_{cd}}\right) = \mp e^{-2i\beta}. \qquad (23)$$

The first CKM factor in (23) comes from (q/p) and the second from $\bar{A}_{\psi K}/A_{\psi K}$. The $\mp$ signs are related to the CP eigenvalue of the final state. One obtains [11,13,23]

$$S_{\psi K_S} = \mathcal{I}m\lambda_{\psi K_S} = \sin 2\beta = \frac{2\bar{\eta}(1-\bar{\rho})}{\bar{\eta}^2 + (1-\bar{\rho})^2}. \qquad (24)$$

This is the constraint that has been used in our unitarity triangles. Note that there are no hadronic parameters involved in the translation of the experimental value of $S_{\psi K_S}$ to an allowed region in the $(\bar{\rho}, \bar{\eta})$ plane. Hadronic uncertainties arise only below the percent level.

Our CKM fit yields, for example, the following allowed ranges (at CL> 32%):

$$0.12 \le \bar{\rho} \le 0.35, \qquad 0.28 \le \bar{\eta} \le 0.41,$$
$$-0.82 \le \sin 2\alpha \le 0.24, \qquad 40^o \le \gamma \le 73^o. \qquad (25)$$

- Approximate CP is excluded. Approximate CP has been one of the more intriguing alternatives to the KM mechanism. It assumes that ε

and ε' are small not because of flavor suppression, as is the case with the KM mechanism, but because all CP violating phases are small. This idea can be realized (and is well motivated) within the supersymmetric framework [24–28]. However, the observation of a CP asymmetry of order one excludes this idea. (One can still write viable models of approximate CP, but these involve fine-tuning.) Similarly, minimal left-right-symmetric models with spontaneous CP violation [29–31] are excluded.

• New, CP violating physics that contributes $> 20\%$ to $B^0 - \overline{B^0}$ mixing is disfavored. As mentioned above, it is still possible that there is a significant new physics in $B^0 - \overline{B^0}$ mixing, but the new phase and the Standard Model β (different from the Standard Model fit) conspire to give an asymmetry that is the same as predicted by the Standard Model. This situation is rather unlikely, but is not rigorously excluded.

3.3. $B \to \phi K_S$ and $B \to \eta' K_S$

The $B \to \phi K_S$ and $B \to \eta' K_S$ decays, related to the $\bar{b} \to \bar{s} s \bar{s}$ quark transition, are dominated by a single weak phase. An amplitude carrying a second, different phase, is suppressed by a CKM factor of $\mathcal{O}(\lambda^2)$. Consequently, the deviation of $|\bar{A}/A|$ from unity is predicted to be at the few ($\lesssim 4$) percent level [32,33]. It is then expected that $|\lambda_{\phi K}| = |\lambda_{\eta' K}| = 1$ to a good approximation. These modes belong then to the 'clean' class described above: $S \simeq \mathcal{I}m\lambda$ and can be cleanly interpreted in terms of the difference between the phase of the $B^0 - \overline{B^0}$ mixing amplitude and twice the phase of the $b \to s\bar{s}s$ decay amplitude.

Averaging over the new Belle [3] and Babar [4] results for the ϕK_S mode, we obtain the present world average,

$$\begin{aligned} C_{\phi K_S} &= +0.56 \pm 0.43, \\ S_{\phi K_S} &= -0.39 \pm 0.41. \end{aligned} \tag{26}$$

The new Belle results for the $\eta' K_S$ mode [3] read

$$\begin{aligned} C_{\eta' K_S} &= -0.26 \pm 0.22, \\ S_{\eta' K_S} &= -0.76 \pm 0.36. \end{aligned} \tag{27}$$

Thus, CP violation in $b \to s\bar{s}s$ transitions has not yet been observed.

In spite of being related to a different quark transition, the CKM dependence of these two modes is the same [up to $\mathcal{O}(\lambda^2)$ effects] as that of $\lambda_{\psi K}$ of eq. (23). Consequently, within the Standard Model,

$$S_{\phi K_S} \simeq -S_{\eta' K_S} \simeq S_{\psi K_S}. \tag{28}$$

A difference (larger than a few percent) between the CP asymmetries in the ϕK_S or $\eta' K_S$ modes and in the ψK_S mode is a clear signal of new physics [34]. More specifically, such a difference requires that new, CP violating physics contributes significantly to $b \to s$ transitions.

The measurements of the two modes suffer from large statistical errors. At present, there is no evidence (*i.e.*, an effect $\geq 3\sigma$) for either $S_{\phi K_S} \neq S_{\psi K_S}$ or $-S_{\eta' K_S} \neq S_{\psi K_S}$. We conclude that, at present, there is no evidence for new physics in these measurements.

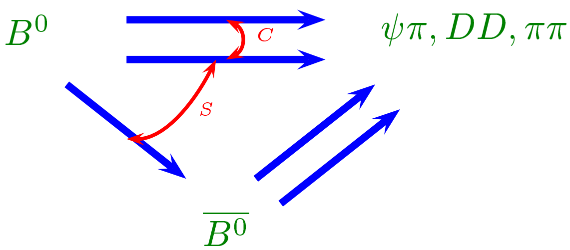
One might be tempted to interpret the 2.7σ difference between $S_{\phi K_S}$ and $S_{\psi K_S}$ as a *hint* for new physics. It would be rather puzzling, however, (though, perhaps, not impossible) if new, CP violating physics affects $B \to \phi K_S$ in a dramatic way but gives only a very small effect in $B \to \eta' K_S$. Furthermore, Belle has also searched for CP violation in $B \to K^+ K^- K_S$ decays (with the ϕ-resonance contributions removed) [3]:

$$\begin{aligned} C_{K^+K^-K_S} &= +0.42 \pm 0.37^{+0.22}_{-0.03}, \\ S_{K^+K^-K_S} &= -0.52 \pm 0.47^{+0.03}_{-0.27}. \end{aligned} \tag{29}$$

(This is a-priori not a CP eigenstate, but a combination of experimental data and isospin considerations allows Belle to conclude that the final state is dominantly CP-even. The last, asymmetric, error is related to the fractions of CP-even and CP-odd components.) We learn that there is no observed deviation from $-S_{K^+K^-K_S} = S_{\psi K_S}$. We would like to suggest then that, when speculating on the source of the difference between $S_{\phi K_S}$ and $S_{\psi K_S}$, one should also explain the difference between the $S_{\phi K_S}$ and the other $b \to s\bar{s}s$ processes, $-S_{\eta' K_S}$ and $-S_{K^+K^-K_S}$. (Of course, the large statistical errors make any conclusion premature).

3.4. $B \to \psi\pi^0$ and $B \to D^{*+}D^{*-}$

The $B \to \psi\pi^0$ and $B \to D^{*+}D^{*-}$ decays, related to the $\bar{b} \to \bar{c}c\bar{d}$ quark transition, get contributions from both tree and penguin diagrams, where the CKM combinations are of similar magnitude, $\mathcal{O}(\lambda^3)$, but carry different phases. Consequently, the deviation of $|\bar{A}/A|$ from unity can be large. Since both C and, in particular, S can be large, CP violation in mixing can be safely neglected.



Averaging over the new Belle [3] and Babar [4] results for the $\psi\pi^0$ mode, we obtain the present world average,

$$\begin{aligned} C_{\psi\pi} &= +0.31 \pm 0.29, \\ S_{\psi\pi} &= -0.46 \pm 0.49. \end{aligned} \tag{30}$$

The $D^{*+}D^{*-}$ state is not a CP eigenstate. The Babar collaboration has, however, performed an angular analysis which separates the CP-even and CP-odd components, with the following result for the CP-even final state [3]:

$$\begin{aligned} |\lambda_{(D^{*+}D^{*-})_+}| &= 0.98 \pm 0.27, \\ \mathcal{I}m\lambda_{(D^{*+}D^{*-})_+} &= 0.31 \pm 0.46. \end{aligned} \tag{31}$$

Thus, CP violation in $b \to c\bar{c}d$ transitions has not yet been observed.

The CKM dependence of the tree contribution to λ in $b \to c\bar{c}d$ transitions is the same as that of $\lambda_{\psi K}$ of eq. (23). Loop contributions, however, modify the CKM dependence. Defining T and P through

$$A_f \equiv T_f V_{cb}^* V_{cd} + P_f V_{tb}^* V_{td}, \tag{32}$$

we obtain

$$\lambda_{f_\pm(\bar{c}c\bar{d}d)} = \pm e^{-2i\beta}\left(\frac{1+(P_f R_t/T_f)e^{+i\beta}}{1+(P_f R_t/T_f)e^{-i\beta}}\right). \tag{33}$$

Consequently, a violation of either $-S_{\psi\pi} = S_{\psi K_S}$ or $-S_{(DD)_+} = S_{\psi K_S}$ will signal direct CP violation and, in particular, a significant penguin contribution to the decay. (If the violation is very strong, it might signal new physics. This statement is particularly valid for the DD mode, where the penguin contribution is expected to be small.)

The measurements of the two modes suffer from large statistical errors. At present, there is no evidence for either $-S_{\psi\pi} \neq S_{\psi K_S}$ or $-S_{D^*D^*} \neq S_{\psi K_S}$. We conclude that, at present, there is no evidence for 'penguin pollution' in these measurements.

3.5. $B \to \pi\pi$

The $B \to \pi\pi$ decay, related to the $\bar{b} \to \bar{u}u\bar{d}$ quark transition, gets contributions from both tree and penguin diagrams, where the CKM combinations are of similar magnitude, $\mathcal{O}(\lambda^3)$, but carry different phases. Consequently, the deviation of $|\bar{A}/A|$ from unity can be large. Since both C and, in particular, S can be large, CP violation in mixing can be safely neglected.

The results of Belle (based on 41.8 fb^{-1} [35] and not updated in this conference) and Babar [4] for CP violation in $B \to \pi\pi$ suffer from large statistical errors and are inconsistent with each other. It is, therefore, more prudent at present to quote the separate results rather than average over them:

$$\begin{aligned} C_{\pi\pi} &= \begin{cases} -0.94^{+0.31}_{-0.25} \pm 0.09 & \text{Belle}, \\ -0.30 \pm 0.25 \pm 0.04 & \text{Babar}, \end{cases} \\ S_{\pi\pi} &= \begin{cases} -1.21^{+0.38+0.16}_{-0.27-0.13} & \text{Belle}, \\ +0.02 \pm 0.34 \pm 0.05 & \text{Babar}. \end{cases} \end{aligned} \tag{34}$$

Defining T and P through

$$A_{\pi\pi} \equiv T_{\pi\pi} V_{ub}^* V_{ud} + P_{\pi\pi} V_{cb}^* V_{cd}, \tag{35}$$

we obtain

$$\lambda_{\pi\pi} = e^{2i\alpha}\left(\frac{1+(P_{\pi\pi}/T_{\pi\pi}R_u)e^{+i\gamma}}{1+(P_{\pi\pi}/T_{\pi\pi}R_u)e^{-i\gamma}}\right). \tag{36}$$

The (expected) violation of $-S_{\pi\pi} = S_{\psi K_S}$ or of $C_{\pi\pi} = 0$ will signal direct CP violation. At

Table 1
CP asymmetries in $B \to f_{\rm CP}$.

$f_{\rm CP}$	$b \to q\bar{q}q'$	SM	S	C	$-\eta_{\rm CP} S \neq S_{\psi K}$?$^{(1)}$
ψK_S	$b \to c\bar{c}s$	$\sin 2\beta$	$+0.734 \pm 0.054$	$\vert\lambda\vert = 0.95 \pm 0.04$	
ϕK_S	$b \to s\bar{s}s$	$\sin 2\beta$	-0.39 ± 0.41	$+0.56 \pm 0.43$	2.7σ
$\eta' K_S$	$b \to s\bar{s}s$	$\sin 2\beta$	$+0.76 \pm 0.36$	-0.26 ± 0.22	$-$
$K^+K^-K_S{}^{(2)}$	$b \to s\bar{s}s$	$\sin 2\beta$	-0.52 ± 0.47	$+0.42 \pm 0.37$	$-$
$\psi\pi^0$	$b \to c\bar{c}d$	$\sin 2\beta_{\rm eff}$	-0.46 ± 0.49	$+0.31 \pm 0.29$	$-$
$D^{*+}D^{*-(3)}$	$b \to c\bar{c}d$	$\sin 2\beta_{\rm eff}$	$\mathcal{I}m\lambda = +0.31 \pm 0.46$	$\vert\lambda\vert = 0.98 \pm 0.27$	2.7σ
$\pi^+\pi^-$	$b \to u\bar{u}d$	$\sin 2\alpha_{\rm eff}$	-0.48 ± 0.60	-0.54 ± 0.31	$-$

$^{(1)}\eta_{\rm CP} = +(-)1$ for CP even (odd) states.
$^{(2)}$Isospin analysis was used to argue that $K^+K^-K_S$ is dominated by CP-even states.
$^{(3)}$Angular analysis was used to separate CP-even and CP-odd $D^{*+}D^{*-}$ states.

present, however, there is no evidence for either of these options. (The average of the two measurements, with errors reflecting the inconsistency, is $C_{\pi\pi} = -0.54 \pm 0.31$ and $S_{\pi\pi} = -0.48 \pm 0.60$.)

The CP asymmetries in $B \to \pi\pi$ decays are one of the most interesting measurements anticipated in the B-factories because it can potentially determine the angle α, thus providing yet another independent constraint on the unitarity triangle. As can be seen from eq. (36), if the penguin contributions were negligible, one would simply have $\mathcal{I}m\lambda_{\pi\pi} = \sin 2\alpha$. The ratio $P_{\pi\pi}/T_{\pi\pi}$ is, however, non-negligible. To proceed, one can choose one of the following options:

1. *A model independent determination of α from isospin analysis* [36]. This method requires measurements of various branching fractions and CP asymmetries and does not yet yield useful constraints.

2. *A model independent upper bound on the deviation of* $\sin 2\alpha_{\rm eff} \equiv \frac{\mathcal{I}m\lambda_{\pi\pi}}{|\lambda_{\pi\pi}|}$ *from* $\sin 2\alpha$ [37,38]:

$$\sin^2(\alpha_{\rm eff} - \alpha) \leq \frac{\mathcal{B}(B \to \pi^0\pi^0)}{\mathcal{B}(B^+ \to \pi^+\pi^0)} \leq 0.6. \qquad (37)$$

Thus $(\alpha_{\rm eff} - \alpha)$ in the range $50^o - 130^o$ is excluded, a useful though not very strong bound.

3. *A model dependent determination of α with a theoretical value for $P_{\pi\pi}/T_{\pi\pi}$* [39,40]. In this context we would like to mention that a large (small) value of $|C_{\pi\pi}|$ would (might) give evidence for a large (small) strong phase, in contrast to the prediction of [39] ([41]).

In the future, measurements of CP violation in $B \to \rho\pi$ decays will contribute to a model independent determination of α [42–44]. The first experimental steps towards this goal have been reported in this conference [4].

3.6. Summary

The results of the searches for CP asymmetries in B decays into final CP eigenstates are summarized in Table 1. We can describe the emerging picture as follows:

- CP violation has not yet been observed in B decays other than $B \to \psi K$. (The largest effect is at the 2.1σ level in $S_{\eta' K_S}$.)

- Direct CP violation has not yet been observed in B decays. (The largest effects are at the 2.7σ level in $S_{\phi K} - S_{\psi K}$ and in $S_{DD} + S_{\psi K}$.)

- There is no evidence of new physics. (The largest effect that is inconsistent with the Standard Model prediction in a 2.7σ violation of $S_{\phi K} = S_{\psi K}$.)

- The measurements of branching ratios and CP asymmetries in $B \to \pi\pi$ decays are at a stage where restrictions on the CKM parameters and on hadronic parameters begin to emerge. The model independent constraints are still mild.

4. New Physics Lessons

CP violation is an excellent probe of new physics. First, the uniqueness of the Kobayashi-Maskawa mechanism (with its single source of CP violation) means that the mechanism is predictive and testable, and that new sources of flavor and CP violation can induce large deviations from the Standard Model predictions. Second, the cleanliness of the theoretical interpretation of various CP asymmetries means that signals of new physics will not be obscured by hadronic uncertainties.

The supersymmetric Standard Model provides an impressive example of the rich possibilities for the physics of CP violation. The model depends on 124 independent parameters, many of which are flavor violating. In particular, 44 of the parameters are CP violating. Consequently, Standard Model correlations between CP violating observables may be violated, and Standard Model zeros in CP asymmetries may be lifted. We use supersymmetry here as an example of new physics that allows us to ask two questions:

- What are the implications of existing measurements of CP violation on supersymmetric model building?
- What are the prospects that future measurements of CP violation will discover deviations from the Standard Model predictions?

4.1. SUSY model building

If all flavor violating and CP violating parameters of the supersymmetric Standard Model were of order one, then constraints from flavor changing neutral current processes and from CP violation would be violated by many orders of magnitude. This statement is best demonstrated when comparing the supersymmetric contribution to the imaginary part of the $K^0-\overline{K^0}$ mixing amplitude to the experimental constraint (derived from $\Delta m_K\times\varepsilon$, see for example [45]):

$$\frac{(\mathcal{I}m M_{12}^K)^{\rm SUSY}}{(\mathcal{I}m M_{12}^K)^{\rm EXPT}} \sim 10^8\,\frac{m_Z^2}{\tilde m^2}\,\frac{\Delta m^2_{\tilde Q}}{m^2_{\tilde Q}}\,\frac{\Delta m^2_{\tilde D}}{m^2_{\tilde D}} \times \mathcal{I}m[(K^d_{LL})_{12}(K^d_{RR})_{12}], \quad (38)$$

where $\tilde m$ is the scale of the soft SUSY breaking terms, $\Delta m^2_{\tilde Q(\tilde D)}$ is the mass-squared difference between the first two doublet (singlet) down squark generations, $m_{\tilde Q(\tilde D)}$ is their average mass, and $K^d_{LL(RR)}$ is the mixing matrix for doublet (singlet) down squarks. Even when one allows for squark and gluino masses close to 300 GeV and for approximate degeneracy induced by RGE effects ($\Delta m^2/m^2\sim 0.15$), the bound is violated by $4-5$ orders of magnitude. Consequently, K physics has had a huge impact on SUSY model building. Eq. (38) shows the various ways in which *the supersymmetric ε problem* can be solved:

- Heavy squarks: $\tilde m \gg 100\ GeV$;
- Universality: $\Delta m^2_{\tilde s\tilde d}\ll \tilde m^2$;
- Alignment: $|K^d_{12}|\ll 1$;
- Approximate CP: $\sin\phi\ll 1$, where ϕ stands for a CP violating phase.

Any viable model of supersymmetry employs one of these options or some combination of them.

The scenario where all CP violating phases are small has been well motivated within the supersymmetric framework. The reason is that even if one employs, say, exact universality to solve all supersymmetric flavor-changing CP problems, there remains a supersymmetric flavor-diagonal CP problem [46]. This statement is best demonstrated by comparing the supersymmetric contribution to the electric dipole moment (EDM) of the neutron with the experimental bound:

$$\frac{d_N^{\rm SUSY}}{6.3\times 10^{-26}\ e\ {\rm cm}} \sim 300\,\frac{m_Z^2}{\tilde m^2}\,\sin\phi_{A,B}. \quad (39)$$

Here ϕ_A (related to the trilinear scalar couplings and gaugino masses) and ϕ_B (related to the bilinear Higgs coupling, bilinear Higgsino coupling and gaugino masses) are the two physical flavor-diagonal phases that remain even in models of exact universality. In this context, the measurement of the CP asymmetry in $B\to\psi K_S$ decays has an immediate impact. Since the measured asymmetry is of order one, it excludes the idea of approximate CP. To solve the *supersymmetric*

EDM problem one has to either assume that the squarks (of at least the first two generations) are heavy or invoke special mechanisms that suppress ϕ_A and ϕ_B but not all flavor-changing CP phases. (It is still possible, but highly unlikely, that the large $S_{\psi K}$ is induced by a small phase, if there are fine-tuned cancellations between various contributions to the real part of the $B^0 - \overline{B^0}$ mixing amplitude.)

Since the measured value of $S_{\psi K}$ is consistent with the Standard Model prediction, it is also consistent with models of exact universality. Such models provide a well motivated example of a class of models where the CKM matrix is the only source of flavor changing and CP violating couplings. This framework is often called '*minimal flavor violation*' (MFV) [47–49] (for recent analyses, see [50,51]). In contrast, the consistency of the measured $S_{\psi K}$ with the Standard Model prediction provides interesting constraints on models with genuinely supersymmetric sources of flavor and CP violation [52]. In particular, models of heavy squarks, where flavor violation is only very mildly suppressed [53], are disfavored.

The search for mixing and CP violation in the neutral D system is the most promising probe of supersymmetric models with alignment. Here, there are two important points concerning CP violation. First, given that it is not impossible for the Standard Model contributions to induce mixing close to present bounds [54], CP violation in mixing is crucial to make a convincing case for new physics [55]. Second, the possible presence of CP violation should be taken into account when translating the experimental bounds into constraints on new physics. Specifically, one obtains [56]

$$|M_{12}^D| \lesssim 5.4 \times 10^{-11}\ MeV, \qquad (40)$$

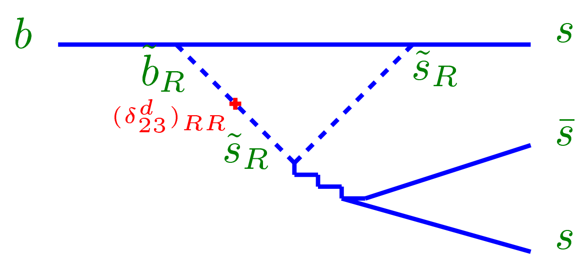
compared to the PDG bound of $2.3\times 10^{-11}\ MeV$ which assumes vanishing weak and strong phases. The bound of eq. (40) implies a severe constraint on squark masses in alignment models [57].

The mechanism by which supersymmetric flavor and CP violation are suppressed relates directly to the mechanism of dynamical supersymmetry breaking. In this sense, if supersymmetry is discovered, measurements of CP violating observables will play a crucial role in understanding the full high-energy theory [58,59]. Future searches for EDMs are important in this context. While supersymmetric models with only the Kobayashi-Maskawa phase as a source of CP violation (such as certain models of gauge mediation) typically give $d_N \lesssim 10^{-31}e$ cm, those where supersymmetry breaking is communicated at or close to the Planck scale typically give $d_N \gtrsim 10^{-28}e$ cm.

4.2. SUSY CP violation in $B \to \phi K_S$?

We choose the question of whether supersymmetry can significantly modify the CP asymmetry in the $B \to \phi K_S$ decay to demonstrate several points that have more general applicability.

Supersymmetry contributes to the $B \to \phi K_S$ decay via, for example, gluonic penguin diagrams with intermediate squarks and gluinos [60,61].



Two crucial questions, regarding the size of this effect, come immediately to mind:

• Is it still possible that new physics has an $\mathcal{O}(1)$ effect on $S_{\phi K}$ when the measured value of $S_{\psi K}$ is so close to the Standard Model prediction?

The answer to this question is positive. Assuming that the consistency is not accidental, it teaches us that the effects of new, CP violating physics in $b \to d$ transitions is small. The $B \to \phi K_S$ decay involves, however, not only $B^0 - \overline{B^0}$ mixing but also the $b \to s\bar{s}s$ decay. There is no similar indication for the smallness of new, CP violating effects in $b \to s$ transitions.

In the language of supersymmetry, the $S_{\psi K}$ constraint applies to δ^d_{13} [52] while $B \to \phi K_S$ depends also on δ^d_{23}.

• Is it still possible that new physics has an $\mathcal{O}(1)$ effect on $S_{\phi K}$ when the measured value of $\mathcal{B}(B \to X_s\gamma)$ is close to the Standard Model prediction?

The answer to this question is, again, positive. The $b \to s\gamma$ rate teaches us that the effects of new, helicity changing physics in $b \to s$ transitions is small. The $B \to \phi K_S$ decay involves, however, also helicity conserving contributions, which are much more weakly constrained [62,63].

In the language of supersymmetry, the $\mathcal{B}(B \to X_s\gamma)$ constraint is significant for δ^d_{LR} while $B \to \phi K_S$ depends also on δ^d_{LL} and δ^d_{RR}.

Having answered these two generic questions in the affirmative, one may ask a third question that is more specific to supersymmetry:

• Are there well motivated supersymmetric models where new, CP violating effects in $b \to s$ transitions could be particularly large?

We are aware of, at least, two classes of models where this is indeed the case. First, in models where an Abelian horizontal symmetry determines the flavor structure of both the quark Yukawa matrices and the squark mass-squared matrices, the supersymmetric mixing angles are related to the quark parameters [64–66]. In particular, we have

$$(\delta^d_{RR})_{23} \sim \frac{m_s/m_b}{|V_{cb}|} = \mathcal{O}(1). \tag{41}$$

Note, however, that if alignment is to solve the supersymmetric flavor problem without any squark degeneracy, $(\delta^d_{RR})_{23}$ must be suppressed compared to the estimate (41). Similarly, in models where a non-Abelian horizontal symmetry determines all flavor parameters, $(\delta^d_{RR})_{23} \ll 1$ and so is the difference between $S_{\phi K}$ and $S_{\psi K}$ [67,68].

Second, in supersymmetric GUT theories, the $b_R - s_R$ mixing is related to the $\nu_\mu - \nu_\tau$ mixing. The latter is required to be of order one to explain the atmospheric neutrino measurements. This intriguing relation has particularly interesting consequences in the framework of $SO(10) \to SU(5)$ theories, where one obtains [69,70]

$$(\delta^d_{RR})_{23} \sim \frac{15}{8\pi^2} \log\frac{M_{\rm Pl}}{M_{10}} = \mathcal{O}(0.5). \tag{42}$$

4.3. Discussion

The general conclusion of the discussion of supersymmetry is that, if the consistency between experiment and the Standard Model concerning $S_{\psi K}$ is not accidental, then large (*i.e.* $\gg 20\%$) CP violating effects in $b \to d$ transitions are disfavored. In contrast, the constraints on new CP violating effects in $b \to s$ transitions are much milder.

We would like to demonstrate this point by performing a premature but, hopefully, thought-provoking exercise. Instead of the "B-triangle" and "K-triangle" of Figure 3, we now divide the loop processes (sensitive to new physics) into three classes. First, those involving $s \to d$ flavor-changing neutral current (FCNC) transitions. This triangle is identical to the K-triangle presented in Figure 3. Second, processes involving $b \to d$ FCNC transitions. Here we include only Δm_B and $S_{\psi K}$. Finally, the constraints that arise from the lower bound on $\Delta m_{B_s}/\Delta m_{B_d}$ and from the bounds on $S_{\phi K_S}$. Both constraints involve, in addition to the $B^0 - \bar{B}^0$ mixing amplitude, $b \to s$ FCNC transitions. The results of this exercise are presented in Figure 4.

There is one solid statement that can be made on the basis of this presentation: *There is still a lot to be learnt from future measurements.* In particular, the probing of new physics in FCNC and in CP violating processes will become much more sensitive when the following is achieved:

• The $b \to d$ triangle: The experimental accuracy and theoretical understanding of B decays that depend on α, γ, $|V_{ub}|$ and $|V_{cb}|$ improve.

• The $s \to d$ triangle: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ is measured more precisely and the CP violating $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$ is measured [71–74].

• The $b \to s$ triangle: The CP asymmetries in $B \to \phi K_S$ and other $b \to s\bar{s}s$ processes are measured more precisely and Δm_{B_s} and CP asymmetries in B_s decays are measured.

• Standard Model zeros: The experimental sensitivities to CP violation in $D^0 - \overline{D^0}$ mixing and to EDMs improve.

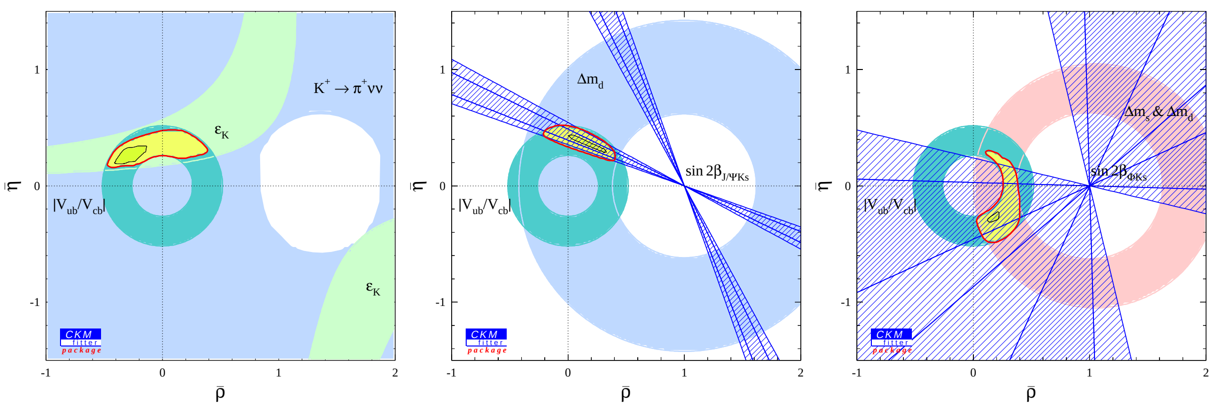


Figure 4. Unitarity triangle constraints from tree level decays and from (left) $s \to d$, (center) $b \to d$, and (right) $b \to s$ loop processes.

5. Conclusions

We have made a significant progress in our understanding of CP violation. For the first time, we are able to make the following statement based on experimental evidence:

• *Very likely, the Kobayashi-Maskawa mechanism is the dominant source of CP violation in flavor changing processes.*

One consequence of this development is the following:

• We are leaving the era of hoping for new physics *alternatives* to the CKM picture of flavor and CP violation.

In particular, the superweak scenario is excluded by the observation of direct CP violation in $K \to \pi\pi$ decays, and the scenario of approximate CP is excluded by the observation of an order one CP asymmetry in $B \to \psi K_S$ decays.

• We are entering the era of seeking for new physics *corrections* to the CKM picture.

This effort would require a broad experimental program, and improvements in both the experimental accuracy and the theoretical cleanliness of CKM tests.

One has also to bear in mind that rather large corrections are still possible in Δm_{B_s}, in CP asymmetries in B_s decays, and in CP asymmetries in B decays related to $\bar{b} \to \bar{s}s\bar{s}$ transitions.

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